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LARGE-AREA SHEET TASK  
ADVANCED DENDRITIC WEB GROWTH DEVELOPMENT

C. S. Duncan, R. G. Seidensticker, and J. P. McHugh

Contract No. 955843

Quarterly Report for the period  
January 1, 1983 to March 31, 1983

The JPL Flat Plate Solar Array Project is sponsored by the U.S. Dept. of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, by agreement between NASA and DOE.

August 15, 1983

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Pittsburgh, Pennsylvania 15235

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APPROVED:



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## 1. SUMMARY

Modeling activity has continued toward the goal of developing new low-stress configurations for wide web growth. Additionally, parametric sensitivity studies have been continued to identify design features that could be used effectively for dynamic trimming of the furnace elements. Extensive temperature measurements and analysis of experimental growth behavior have led to modifications in the growth system which produce improved lateral temperature distributions.

## 2. INTRODUCTION

Silicon dendritic web is a single-crystal silicon ribbon material which provides substantial advantages for the low-cost manufacture of solar cells. Growth from a melt of silicon without the use of constraining dies is a significant feature of the process which results in an oriented single-crystal ribbon having excellent surface characteristics. In common with other more typical processes such as Czochralski growth, impurity rejection into the melt permits the use of less pure "solar grade" starting material without significantly affecting cell performance. A unique property of the dendritic web process is the growth of long ribbons of controllable width and thickness which not only facilitates automation of subsequent processing into solar cells, but also results in high material utilization since cutting and polishing are not required.

On the present contract, three broad areas of work are emphasized:

1. The development of thermal stress models in order to understand the detailed parameters which generate buckling stresses, and the application of these models to the development of new low-stress design concepts.
2. Experiments to increase our understanding of the effects of various parameters on the web growth process and to complement and verify the results of the modeling effort.
3. The construction and utilization of an experimental web growth machine which contains in a single unit all the mechanical and electronic features developed previously so that experiments can be carried out under tightly controlled conditions.

The principal objective of this work has therefore been to expand our knowledge and understanding of both the theoretical and experimental aspects of the web growth process to provide a solid base for substantial improvements in both area throughput and web crystal quality, and to develop the tools necessary to carry out this objective.

During this reporting period, modeling work has been directed toward the development of new low-stress configurations for wide web growth and, in addition, parametric studies have been continued to identify design features which could be used effectively for dynamic trimming of the furnace elements. Experimental work has been concentrated on trimming lateral temperature profiles for improved growth with replenishment and correlating measured shield temperatures and melt position with growth characteristics.



### 3. TECHNICAL PROGRESS

#### 3.1 Thermal Modeling

Modeling activity has continued toward the goal of developing new low-stress configurations for wide web growth. Additionally, parametric sensitivity studies have been continued to identify design features that could be used effectively for dynamic trimming of the furnace elements. Progress has been made in both areas with identification of a new low-stress design which has great potential for wide, unbuckled growth, and a better understanding of the effect of the various growth system elements.

##### 3.1.1 New Growth Configuration

The foundation for the latest in the series of low stress, wide web growth configurations was given in the previous quarterly report.<sup>(1)</sup> The effect of a taller shield stack assembly was obviously to reduce the  $\Delta\sigma_x$  stress peak which occurs near the height where the web crystal exits the shields, and this observation was pursued by adding an additional stack element to generate an assembly almost 6 cm tall. This configuration, now known as the J483 design, generated a very small  $(\alpha T)''$  value in the shield stack region as shown in Figure 1. This is an expanded scale version of the figures presented in previous reports and gives a clearer representation of the variation  $(\alpha T)''$  at small values. The effects of the individual lower elements (lids, shields, spacers) is evident in the first few centimeters; at a higher position, the individual element contributions are too small to be resolved.

The stress calculations based on the same temperature profile as Figure 1 confirmed the anticipated low-stress magnitudes. One of the critical stress parameters,  $\Delta\sigma_x [\sigma_x(\text{center}) - \sigma_x(\text{edge})]$ , is plotted for the

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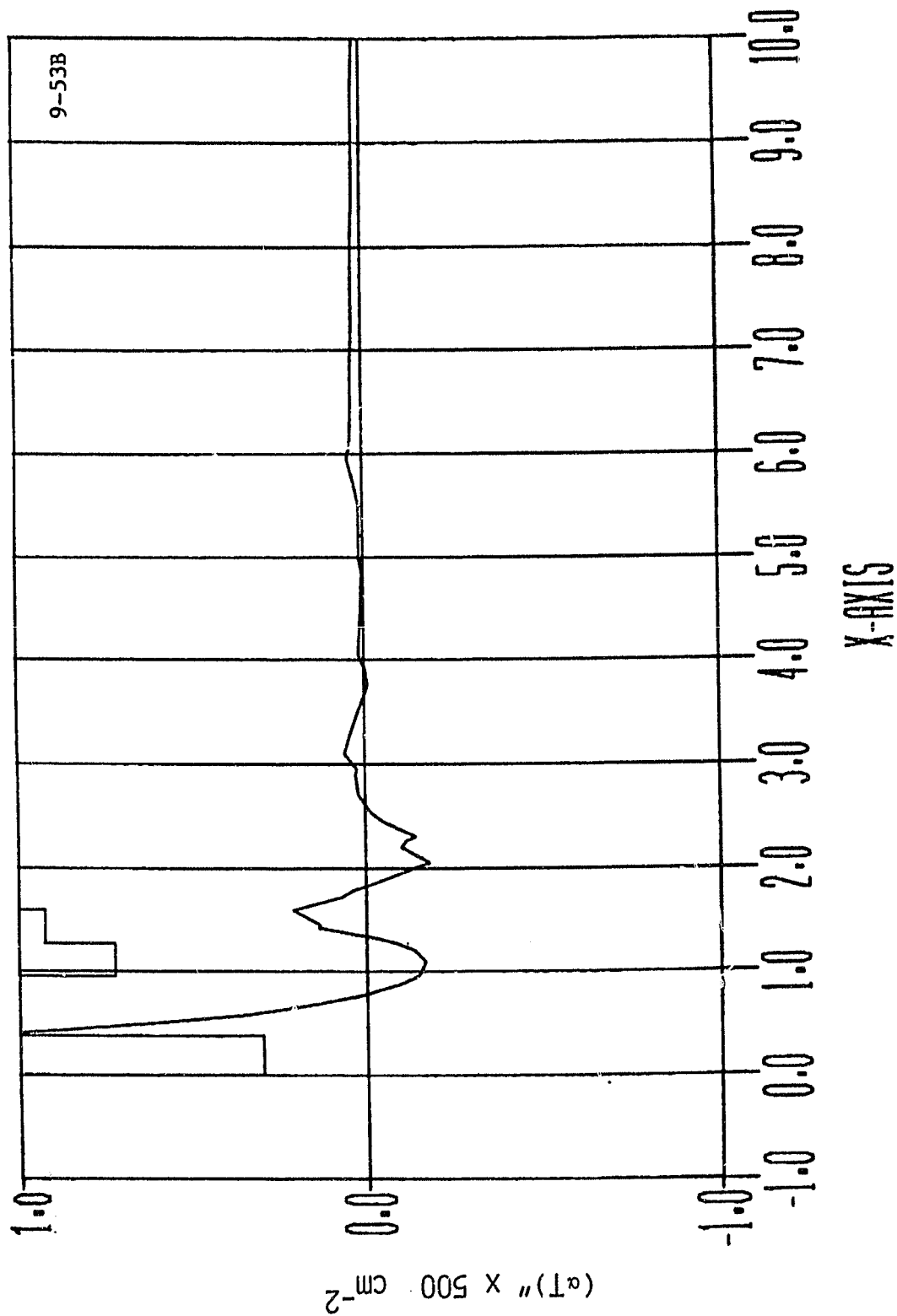


Figure 1 —  $(\alpha T)$  versus position along ribbon for J483 configuration.

J483 geometry in Figure 2; also shown are similar curves for the J98M3A and the J460 geometries. It is readily apparent that the stress calculated for the J483 is significantly less than for the J460 configuration, the best of the prior designs. Both the J460 and the J483 have similar stress peaks in the first centimeter or so, which is reasonable since the lid design is the same for both cases. Further up the ribbon, however, the stress maxima are about  $190 \text{ Mdyn/cm}^2$  for the J460 but only  $93 \text{ Mdyn/cm}^2$  for the J483.

The y-stress distribution also tends to be a maximum near the growth front as shown in Figure 3. Again this distribution is very similar to the corresponding curve for the J460 design. In fact, the magnitude of the maxima and minima in the curve are generally somewhat less than in the J460 case. As yet, an extensive comparison of residual stress data for the J460 and the J483 is not available; however, the low observed residual stress, even in the wide J460 ribbon, suggests that the y-stress should be at an acceptable level in the J483 design.

Once the two-dimensional stress modeling had indicated that the J483 configuration had potential for wider growth through reduced stress, a buckling analysis was performed. Two cases were examined: 9-53B which used the identical temperature profile as in the two-dimensional analysis and modeled a 0.015 cm thick ribbon, and case 9-54B which modeled a 0.030 cm thick ribbon growing from the same growth configuration as 9-53B. In both cases, the model considered a 10 cm length of 3.95 cm wide ribbon.

For the buckling analysis, the computed temperature profiles were used to generate a three-dimensional stress profile which in turn was used as the input to the buckling analysis. That code solves the eigenvalue problem

$$[K] \{\Delta\} = \lambda [Z] \{\Delta\} \quad (1)$$

where  $[K]$  is the stiffness matrix,  $\{\Delta\}$  is the displacement vector, i.e., the deviation of the ribbon from flatness,  $[Z]$  is the stress matrix, and  $\lambda$  is the eigenvalue for the problem. In general, several eigenvalues

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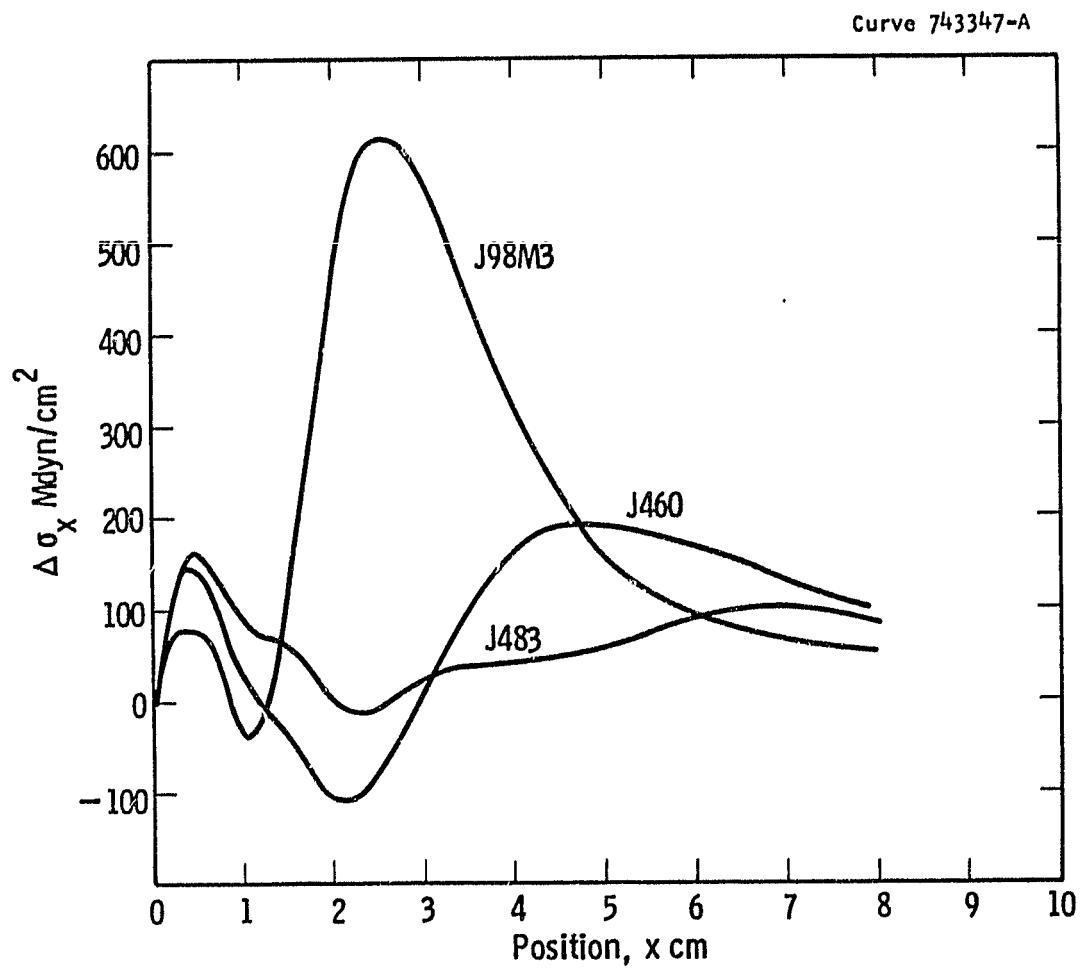


Figure 2 — Delta x-stress versus position along ribbon length for J483 configuration.

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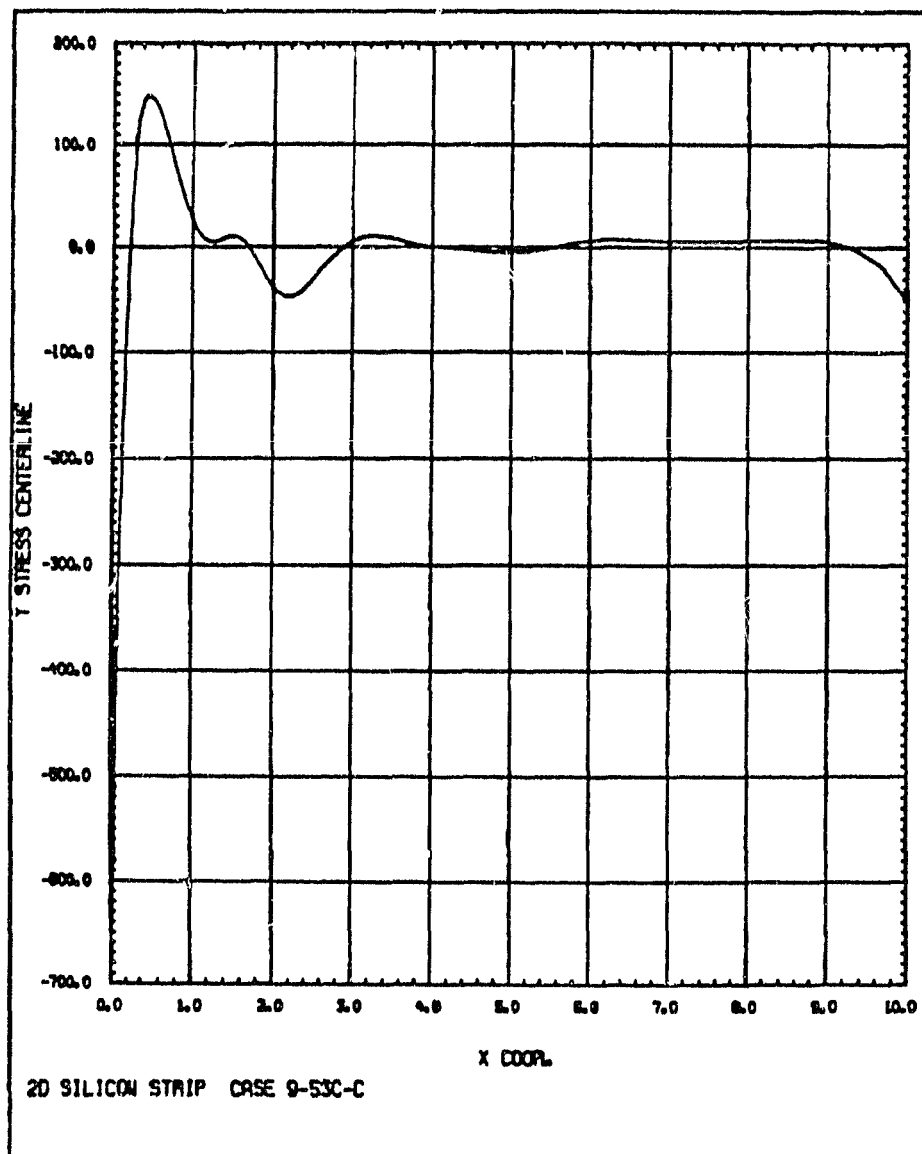


Figure 3 -- Centerline y-stress versus position along ribbon length for J483 configuration.

may be calculated, although only the smallest positive value is of importance for the present purpose. If  $\lambda > 1$ , the ribbon would be undeformed under the stress conditions used for the input, while  $\lambda < 1$  indicates that the ribbon would be buckled.

The results for the two cases are given in Table 1. In both cases, the ribbon would be flat for the conditions of the problem; the question is now under what conditions of width and thickness would  $\lambda = 1$ , indicating the onset of buckling.

We discussed in a previous report<sup>(2)</sup> that the thickness at which the 3.95 cm web would buckle can be estimated by interpolation/extrapolation of the calculated data to find the thickness for which  $\lambda = 1$ . Assuming that  $\lambda \sim t^m$ , the present data gives  $m = 1.335$ , which leads to a critical buckling thickness of .0095 cm for 3.95 cm wide web. For our present purposes, however, the critical thickness is not as important as the critical width at .015 cm thickness. Again, we must resort to extrapolation since there are practical difficulties with our present models in treating web wider than 4 cm. Again, using the previous results of Reference 2, we can assume that  $\lambda \sim w^{-3.63}$ , and on that basis find that the critical width for a 0.015 cm thick ribbon would be 4.7 cm and for a 0.030 cm thick ribbon would be 6.0 cm. Some caution, however, is necessary in accepting these numbers without interpretation since they are based on a specific functional dependence in the extrapolation calculation. Similar calculations would predict that .015 cm thick material grown from a J460 configuration would buckle at 4.0 cm, while in fact crystals about 4.7 cm have been grown at that thickness without deformation. Thus we would expect the J483 configuration to give undeformed ribbons approaching 6 cm wide at .015 cm thickness.

TABLE 1

Model Run No.	Ribbon Width cm	Ribbon Thickness cm	Eigenvalue
9-53B	3.95	.015	1.848
9-54B	3.95	.030	4.662

### 3.1.2 Parametric Design Studies

Modeling the effect of changes in growth system dimensions, temperature, etc. can give guidance not only for the design of new, static configurations, but also for the design of dynamically trimmed or modified assemblies. In the previous quarterly report<sup>(3)</sup> we gave the results of some studies with variations of the J460 design. During the current period, these studies were concluded and parametric studies of the new J483 design were initiated.

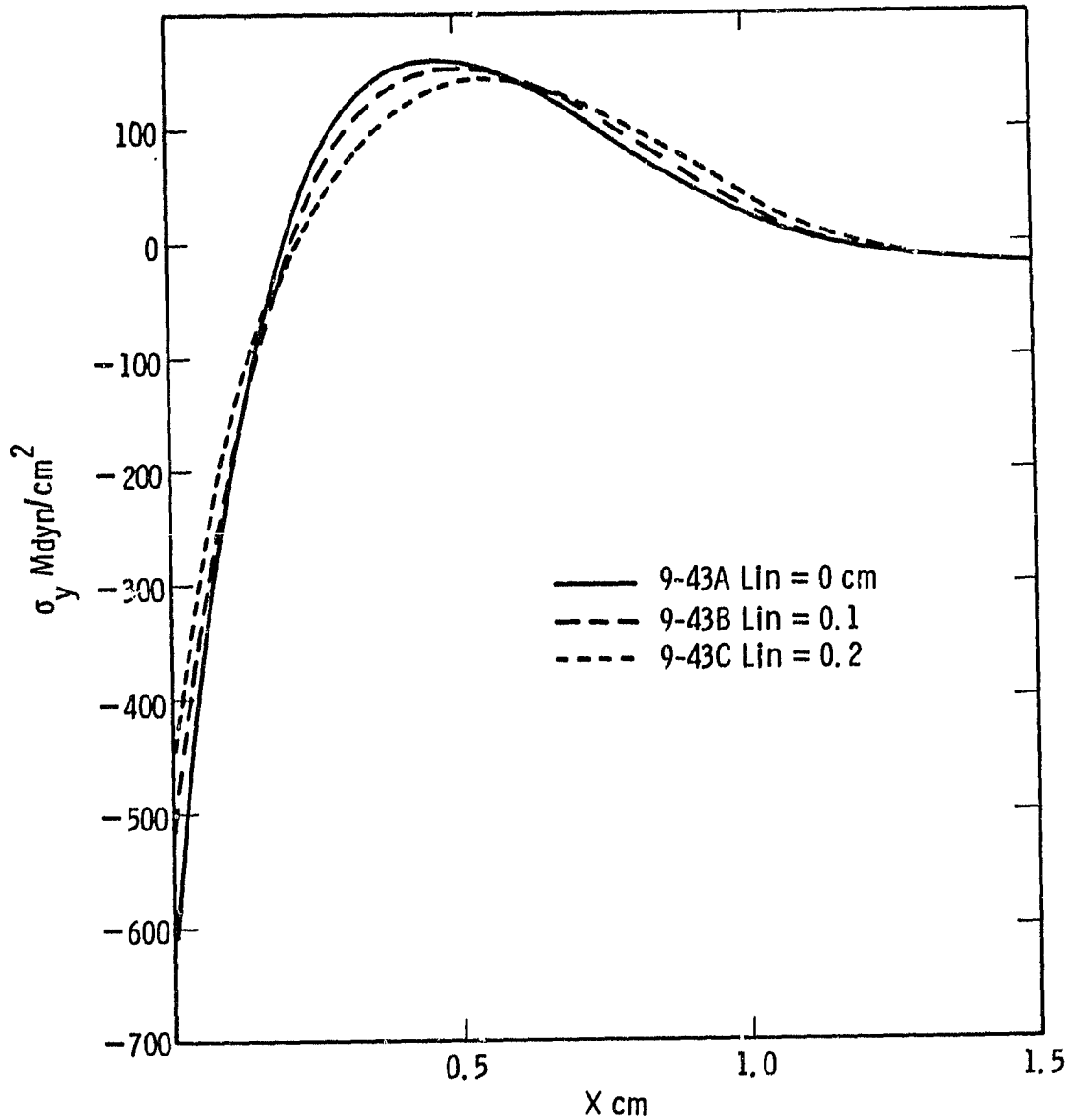
#### 3.1.2.1 J460 Design

The previous work on the J460 configuration indicated that the position of the growth front relative to the susceptor lid (LIN) was a likely parameter for application in a dynamically trimmed growth system. Figure 3 of that report (included here, for completeness, as Figure 4) portrayed the effect of the LIN parameter on the y-stress magnitude along the ribbon centerline in the J460 design. Although there is obviously some change in the y-stress distribution, it is relatively small and interpretation of the effect is difficult because of the complexity of the visco plastic flow mechanism which may be operative.

A somewhat clearer picture is presented in the case of the delta x-stress distribution shown in Figure 5. This stress parameter is the algebraic difference between the x-stress at the ribbon centerline and the stress at the edges, and may be considered as a measure of the tendency for the ribbon to buckle. Although there is a slight change in the shape of the distribution, the major effect of a change in LIN appears to be a simple shifting of the curve commensurate with the change of the growth front position with respect to the lid. The stress peaks themselves thus appear to be relatively fixed with respect to the shield stack. One would not expect much change in buckling behavior with such a shift in the stress distribution, so that one might presume to vary LIN without affecting the tendency of the web crystal to buckle.

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Y-Stress vs position: J460 configuration

Figure 4 -- Y-stress versus position along ribbon for J460 configuration.  
Curves are for different interface positions (LIN).



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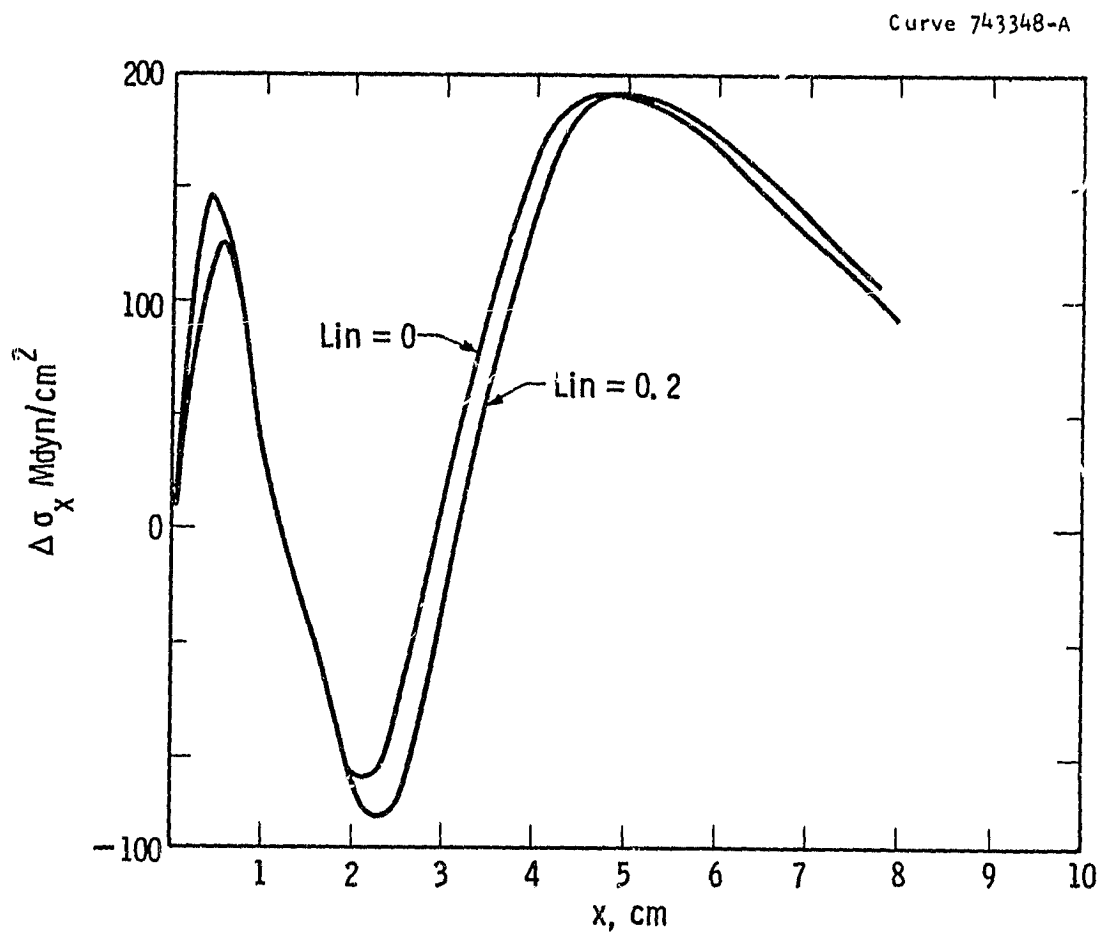


Figure 5 -- Delta x-stress versus position along ribbon for J460 configuration. Curves are for different interface positions (LIN).

The prime motive for using LIN as a dynamic variable is evident in Figure 6, which shows that the web contribution to velocity as a function of LIN changes by about 0.2 cm/min when LIN changes by 0.1 cm. The contribution to the velocity from the supercooled melt also changes in the same way, although the rate of change with LIN is much smaller. It would thus appear that decreasing LIN from its usual value of about 0.2 cm or larger (a recently determined value) would provide distinct benefits in increasing the overall area throughput of web crystals.

#### 3.1.2.2 New Configuration

In addition to modeling the effects of the LIN parameter in the J460 design, a variety of design parameter changes were investigated in other configurations, especially the new, low-buckling stress designs. In the course of the evolution of the J483 design from the J460 configuration, an intermediate concept was developed which had a total lid and shield height of about 5 cm. This design, which was only cursorily tested using J460 hardware, nevertheless served as a baseline case for evaluating some general design variations such as: (1) the slot width in the lid, (2) the lid temperature itself, (3) the temperature of the top shield (with the resulting change in the temperature distribution in the shield stack), and (4) the slot width in the top shield.

The width of the growth slot in the lid is a parameter that has been previously found to influence the growth speed, but the possible effect on the more distant "buckling stress" was not clear. The present results confirm that speed and perhaps residual stress may be the only significant effects of slot width. Narrowing the slot from 6 to 4 mm increased VV (the web velocity component, not the total pull speed) from 1.59 cm/min to 1.67 cm/min, an increase of 5%. Although this change is relatively small, it could represent a useful gain when coupled with other effects. An increase of similar magnitude occurred in the y-stress at the growth front. It should be emphasized, however, that because of the complicated processes involved in the plastic deformation

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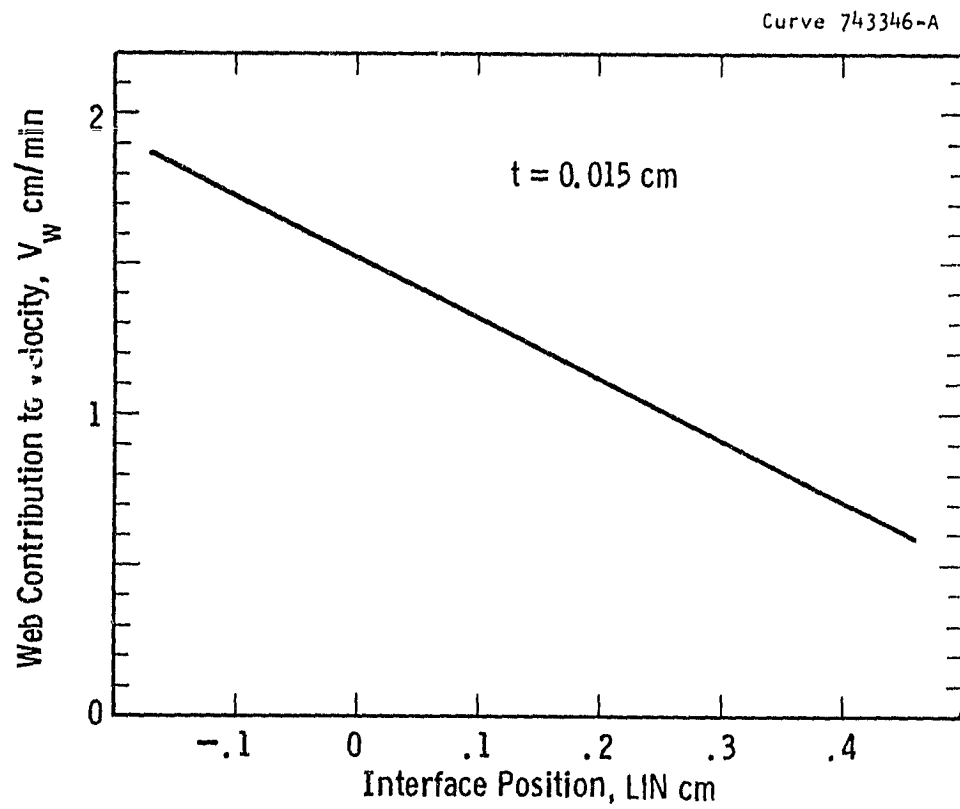


Figure 6 -- Variation of the web contribution to growth velocity with interface position (LIN).

process, the actual effect on residual stress is not easily estimated. All of the observed effects occurred near the growth front, and the "buckling stress" further up the web was unaffected.

The second parameter examined was the temperature of the lid. The lid was assumed to consist of a top section and a bottom section with temperatures of  $1585^{\circ}\text{K}$  and  $1590^{\circ}\text{K}$ , respectively, based on typical thermocouple probe data. A second model run was made assuming these temperatures to be  $1595^{\circ}\text{K}$  and  $1600^{\circ}\text{K}$ . The principal effects of the higher temperatures were to decrease the growth velocity (at  $150\text{ }\mu\text{m}$ ) by 6.3% and the interfacial  $y$ -stress by about 10%; the "buckling stress" was unaffected.

The third parameter examined was the temperature of the top shield (S4) of the four-shield stack. In one modeling run, the normal J460 shield-stack temperature distribution was extrapolated to the higher stack of the present model. This resulted in an S4 temperature of only  $690^{\circ}\text{K}$ , which conceptually seems very small. Surprisingly, this very low top-shield temperature caused only a small increase in the "buckling stress" and had essentially no effect on the growth speed or interfacial  $y$ -stress in comparison with another model run where a more typical top-shield temperature of  $1108^{\circ}\text{K}$  was used. Even with the lower top-shield temperature, the "buckling" stress was much less than for the J460 configuration.

The final parameter checked was the width of the slot in S4. When the slot width was narrowed, however, the "buckling stress" increased with again little effect on either growth speed or interfacial  $y$ -stress.

The results of these studies may be summarized by saying that some parameters have been evaluated which cause changes in particular aspects of the growth. Reasonably enough, those changes near the growth front affect the growth process near the growth front such as growth speed and interfacial  $y$ -stress. Those configuration changes away from the growth front affect the "buckling stress" which occurs further up

the ribbon. Specific elements -- lids or shields -- have major effects on different regions of the temperature profile. In some cases, the interactions are small enough that it should be possible to alter the profile in one region by changing some element parameter without seriously affecting the rest of the temperature distribution.

The effects of changes in the basic J483 design were also investigated; however, the only variation which had a strong effect was the omission of the solid spacers between the top shields. The omission of the spacers resulted in rapid fluctuations in  $(\alpha T)''$  as shown in Figure 7 (compare with Figure 1). The resulting stress distribution indicated a large delta x-stress peak at about 3.5 cm, which is a significant change in magnitude and position compared to the baseline case. This result indicates the sensitivity of the thermal stress generation to design details that might easily be otherwise considered minor.

### 3.2 Experimental Web Growth

Experimental web growth has concentrated on three related activities: 1) management of the lateral temperature distribution in the lids and top shields as well as in the melt, 2) evaluation of new low-stress/wide-growth designs, and 3) the accumulation of quantitative top-shield temperature and melt-level data and the correlation of this information with growth behavior.

#### 3.2.1 Lateral Temperature Distribution

Although the primary requirement for wide web growth is the generation of the proper vertical temperature profile, the lateral temperature profile in the lid and shields, as well as the melt, must also be controlled in order to realize the potential benefits of the low-stress conditions. Experience suggests that the lateral temperature distribution is more important for wide ribbons than it is with narrower ribbons in the 30-35 mm width range, e.g., narrower ribbons are more

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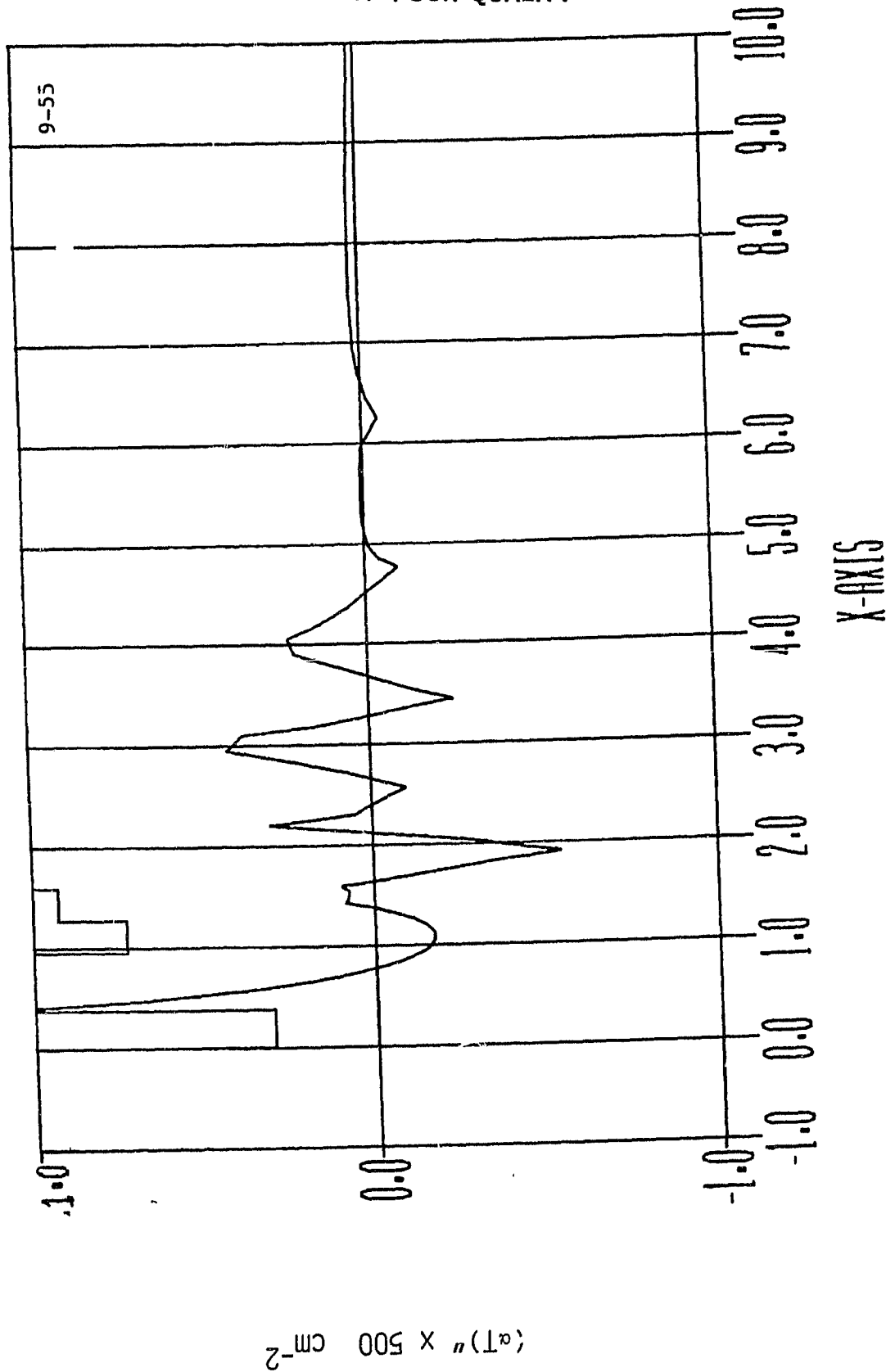


Figure 7 — ( $\alpha T$ )" versus position along ribbon showing effect of removing solid spacers from between top radiation shields.

forgiving of moderate asymmetries. The thermal requirements of melt replenishment impose an additional burden on configuring the growth system for the desired lateral temperature distribution.

The thermal design for producing the desired vertical temperature profiles is guided by the thermal stress models, but the generation of the lateral profiles is largely empirical, guided by experience and experiment. The goal of the lateral temperature trimming is to achieve a relatively flat and particularly symmetric lateral temperature distribution in the growth slot region of the lid, shields, and melt. The means at our disposal include hardware modifications (fixed during a run) and work coil and end shield positioning (variable during a run). Assessment techniques include melt profile measurements, shield temperature measurements and, of course, web growth characteristics such as buttoning behavior, dendrite smoothness, widening behavior, characteristic growth velocity, and residual stress.

Experimental data has been collected on the basic J460, the width-limiting J460L, and to a lesser extent the new J483 low-stress growth configurations. The results of this work generated a number of hardware modifications which serve both to generate a relatively flat symmetric lateral temperature distribution in the melt, lid, and shields and to improve the thermal isolation between the growth and replenishment regions of the melt. These modifications included changes in the susceptor shielding, the movable end shields, and the design of the lids. In addition, the position of one of the crucible barriers was changed.

### 3.2.2 New-Low Stress Configurations

Some preliminary experiments were performed with a new low-stress configuration designated the J479, a design which includes a higher shield stack than the J460 configuration. This design was predicted by the models to generate lower buckling stresses than the J460 design. Before this design could be fully evaluated, however, hardware had been fabricated for an even lower stress design, the

J483. It did not seem productive at this point to continue working to optimize the intermediate J479 design when the better J483 was available, so experimental work was switched to the latter.

Preliminary experiments showed that the temperature profile in the melt generated by the new configuration was more dipped in the center relative to the J460 configuration, so that the web width capabilities of the design could not be exploited. Changes in the susceptor shielding are being made to generate the desired profiles.



#### 4. CONCLUSIONS

Two principal conclusions result from the modeling work discussed in this section. First, the growth system design designated J483 should have sufficiently small thermal stresses to permit the growth of web crystals significantly wider than grown from the J460 configuration. Based on observed growth of up to 5.4 cm web from the J460 system, it is anticipated that 6 to 7 cm web should be grown using the J483 hardware. Second, parametric studies confirm that the melt-to-lid distance,  $L/N$ , is the parameter most likely to be effective in a dynamically trimmed growth system.

## 5. PLANS AND FUTURE WORK

Future modeling activity will concentrate on improving the temperature profile and stress distribution near the growth front of the web crystal. Experimental data on residual stress in the crystals will be used as an aid in interpreting the effects of the calculated stresses. Additionally, hardware will be designed to permit dynamic trimming of the growth systems using variation of the melt-to-lid distance as the adjustable parameter. Experimental work to develop the desired lateral temperature distributions in the J483 configuration will continue.

## 6. NEW TECHNOLOGY

A lid design modification of general applicability has been developed which generates improved lateral temperature profiles in the growth region and improved thermal isolation between end growth and replenishment regions of the melt.

## 7. REFERENCES

1. C. S. Duncan et al., Large-area Sheet Task -- Advanced Dendritic Web Growth Development, DOE/JPL 955843/38/9 (May 22, 1983), p. 9.
2. C. S. Duncan et al., Large-Area Sheet Task -- Advanced Dendritic Web Growth Development Annual Report (March 2, 1982), DOE/JPL-955843/82/1, p. 23.
3. Ref. 1, p. 4.

## 8. ACKNOWLEDGEMENTS

We wish to thank H. C. Foust, W. B. Stickel, and W. Chalmers for their contributions to the web growth studies, and Georgia Law and Debbie Todd for the editing and typing, respectively.

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## 9. PROGRAM COSTS

### 9.1 Updated Program Plan (see pp. 26-28

- 9.1.1 Milestone Chart
- 9.1.2 Program Labor Summary
- 9.1.3 Program Cost Summary

### 9.2 Man-Hours and Costs

#### 9.2.1 Man-Hours:

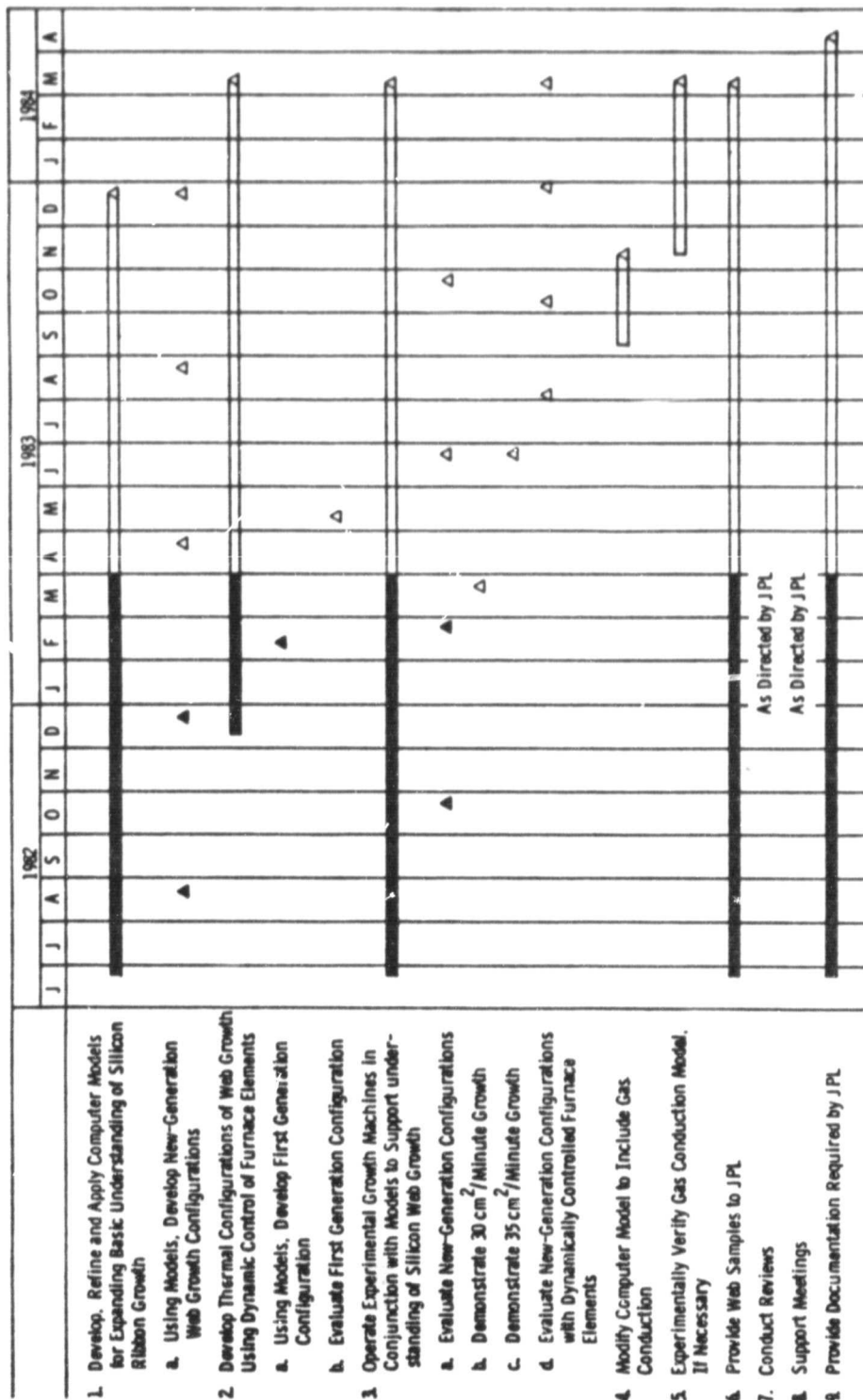
Previous 32,939 hrs.  
This Quarter 2,758 hrs.  
Total 35,697 hrs.

#### 9.2.2 Costs:

Previous \$1,518,011  
This Quarter \$173,536  
Total \$1,691,547

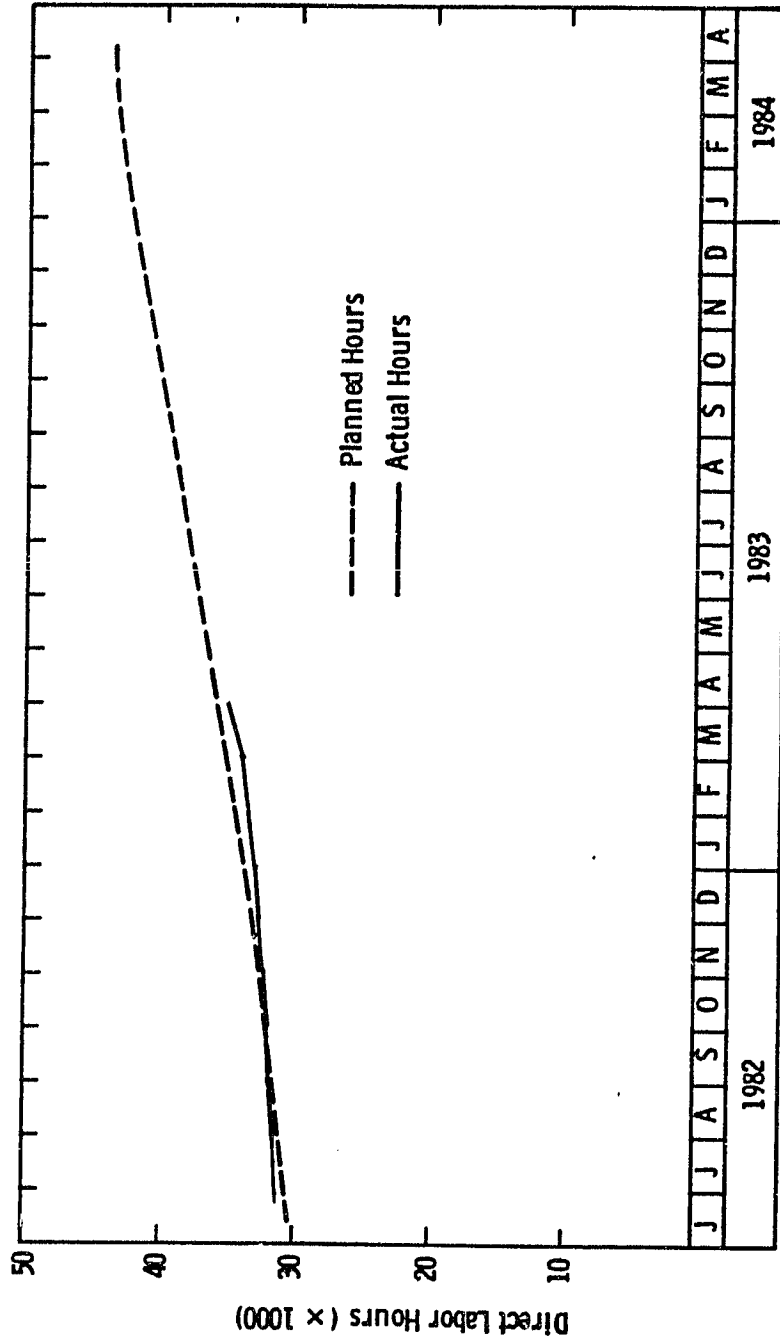
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ADVANCED DENDRITIC WEB GROWTH DEVELOPMENT  
MILESTONE CHART - JPL CONTRACT 955843, MOD. 12

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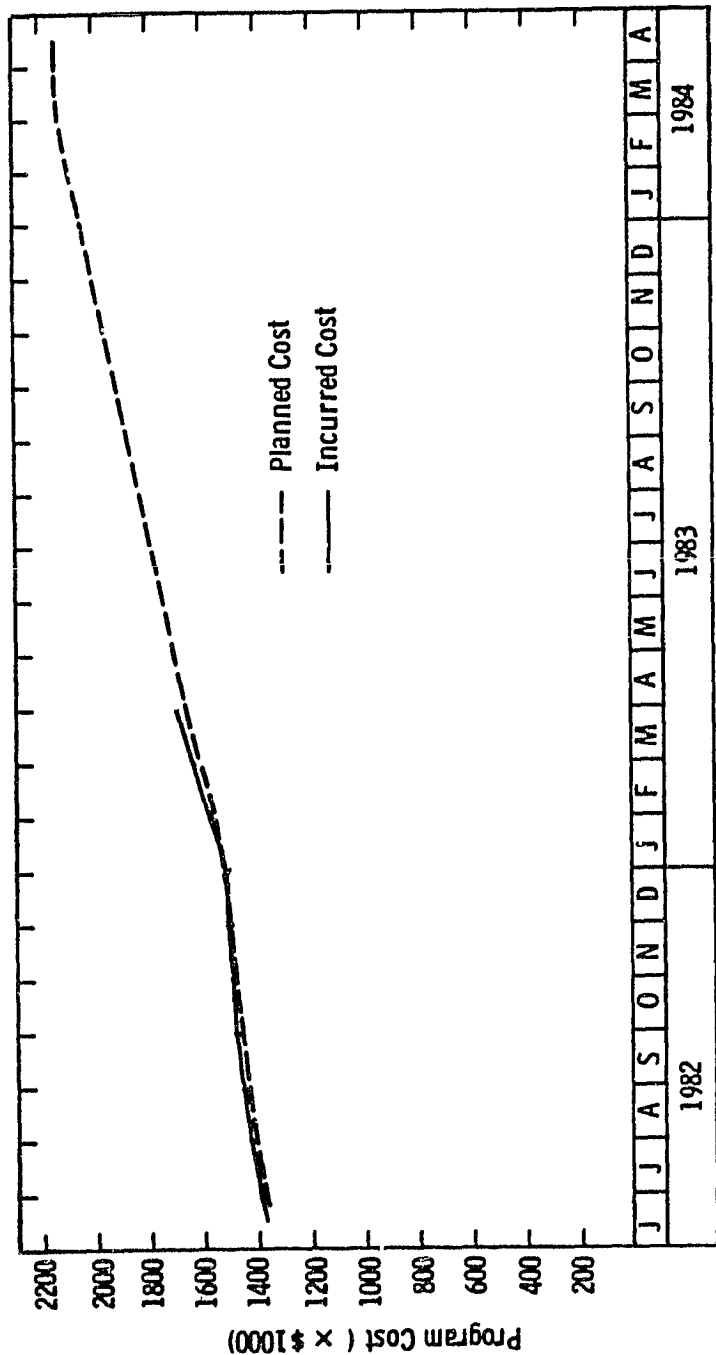
PROGRAM LABOR SUMMARY  
JPL CONTRACT 955843, MOD. 12





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PROGRAM COST SUMMARY  
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Contract Months